

CALiPER

Application Summary Report 17: LED AR111 Lamps

August 2012

Prepared for:

Solid-State Lighting Program

Building Technologies Program
Office of Energy Efficiency and
Renewable Energy
U.S. Department of Energy

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Laboratory

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PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

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(8/2010)

1 Preface

The U.S. Department of Energy (DOE) CALiPER program has been purchasing and testing general illumination solid-state lighting (SSL) products since 2006. CALiPER relies on standardized photometric testing (following the Illuminating Engineering Society of North America [IES] approved method LM-79-08¹) conducted by accredited, independent laboratories.² Results from CALiPER testing are available to the public via detailed reports for each product or through summary reports, which assemble data from several product tests and provide comparative analyses.³

It is not possible for CALiPER to test every SSL product on the market, especially given the rapidly growing variety of products and changing performance characteristics. Starting in 2012, each CALiPER summary report focuses on a single product type or application. Products are selected with the intent of capturing the current state of the market—a cross section ranging from expected low to high performing products with the bulk characterizing the average of the range. The selection does not represent a statistical sample of all available products. To provide further context, CALiPER test results may be compared to data from LED Lighting Facts,⁴ ENERGY STAR® performance criteria,⁵ technical requirements for the DesignLights™ Consortium (DLC) Qualified Products List (QPL),⁶ or other established benchmarks. CALiPER also tries to purchase conventional (i.e., non-SSL) products for comparison, but because the primary focus is SSL, the program can only test a limited number.

It is important for buyers and specifiers to reduce risk by learning how to compare products and by considering every potential SSL purchase carefully. CALiPER test results are a valuable resource, providing photometric data for anonymously purchased products as well as objective analysis and comparative insights. However, LM-79-08 testing alone is not enough to fully characterize a product—quality, reliability, controllability, physical attributes, warranty, compatibility, and many other facets should also be considered carefully.

For more information on the DOE SSL program, please visit <http://www.ssl.energy.gov>.

¹ IES LM-79-08, *Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products*, covers LED-based SSL products with control electronics and heat sinks incorporated. For more information, visit <http://www.iesna.org/>.

² CALiPER only uses independent testing laboratories with LM-79-08 accreditation that includes proficiency testing, such as that available through the National Voluntary Laboratory Accreditation Program (NVLAP).

³ CALiPER summary reports are available at <http://www.ssl.energy.gov/reports.html>. Detailed test reports for individual products can be obtained from <http://www.ssl.energy.gov/search.html>.

⁴ LED Lighting Facts is a program of the U.S. Department of Energy that showcases LED products for general illumination from manufacturers who commit to testing products and reporting performance results according to industry standards. The DOE LED Lighting Facts program is separate from the Lighting Facts label required by the Federal Trade Commission (FTC). For more information, see <http://www.lightingfacts.com>.

⁵ ENERGY STAR is a federal program promoting energy efficiency. For more information, visit <http://www.energystar.gov>.

⁶ The DesignLights Consortium Qualified Products List is used by member utilities and energy-efficiency programs to screen SSL products for rebate program eligibility. For more information, visit <http://www.designlights.org/>.

2 Report Summary

This report analyzes the independently tested performance of six LED products labeled as AR111 or PAR36 lamps. The test results indicate that this product category is lagging behind other types of directional LED Lamps (e.g., PAR30, BR30). For example, the maximum lumen output was only 588 lumens and efficacy ranged from 31 to 58 lm/W. This range in efficacy is notably lower than other similar categories, although still above halogen lamps. Two of the six products had color attributes that were very different from conventional halogen lamps, and none of the LED lamps tested could match the beam angle of the narrowest halogen AR111 lamps.

Given their overall performance characteristics, most—if not all—of the Series 17 LED AR111 lamps are unlikely to be effective replacements for halogen AR111 lamps. This is mostly a result of color quality and luminous intensity distribution characteristics. In some applications, they may perform acceptably—and could provide some energy savings—but continued improvement in this market category is warranted.

Six lamps is a smaller sample compared to other CALiPER application summary reports, and reflects the difficulty in obtaining LED AR111 products. The AR111 form factor is a niche product that is used infrequently in the United States, potentially limiting the market for LED AR111s. Notably, LED AR111 products from many major manufacturers were not available for inclusion in this series of testing.

3 Background

Directional lamps—sometimes referred to as reflector lamps—are an essential tool for both ambient and accent lighting, especially in residential, hospitality, museum, and retail applications. Directional lamps come in many different shapes and have a variety of performance attributes. One type of specialized directional lamp is the AR111—where AR indicates *aluminized reflector*, and 111 indicates a diameter of 111 mm (approximately 4.365 inches). Although AR111 lamps are common in Europe, they are used less frequently in the United States, where R (reflector), BR (bulged reflector),⁷ and PAR (parabolic aluminized reflector) lamps are more prevalent. PAR36 lamps closely resemble AR111s, having a similar base, size, and function, although they also have a limited range of applications. Both AR111 and PAR36 halogen lamps are operated at low-voltage (6 V or 12 V), requiring a transformer as part of the complete lighting system. Notably, AR lamps are not described in ANSI (American National Standards Institute) literature, although PAR36 lamps are included with other directional lamps in ANSI C78.21-2003,⁸ which establishes standard lamp classes.

Despite their small market share, AR lamps are important in certain applications, and are unique because they use a small cap to block direct view of the filament. This shield reduces glare and results in a crisp beam edge because all of the emitted light is oriented by the reflector. The beam control can be especially important in demanding applications.

Halogen AR111 lamps most often have a screw terminal or G53 base. Among other factors, this unique attribute limits their interchangeability with other directional lamp types and makes them rare in the residential market. Because they do not have a medium screw base, AR111 lamps are not considered general service lamps; thus they are excluded from federal energy efficiency regulations.

AR111 (and PAR 36) lamps have a substantially shorter overall length than lamps of comparable diameter. In certain cases, this may be an advantage and may influence the shape of track heads. AR111 lamps also differ from other directional lamps in not having a front lens to enclose the lamp; therefore, they must be used in fully enclosed luminaires if used outdoors. In contrast, PAR36 lamps are *sealed beam*, and can withstand damp environments.

Although AR111s originated as halogen lamps, in recent years a ceramic metal halide (CMH) version has become available. CMH AR111 lamps offer similar high-precision, low-glare light distributions, but have higher efficacy and a longer rated lifetime. Notably, CMH versions utilize a different base and require an external ballast, so they are *not interchangeable with halogen AR111 lamps*. CMH AR111s are addressed in this report because they are an alternative to halogen AR111s in new construction. Despite the fact that they are much more efficacious than halogen products, CMH lamps are limited in application due to long warm-up times, restrike delays, and limited dimming capability.

LEDs are inherently directional, which makes them well suited for use in products intended to replace conventional reflector lamps. The optics can be arranged at the LED package level, reducing the need for reflectors and lenses that shape the beam. However, because they rarely use the same optical system as

⁷ More information on BR- and R-shaped LED lamps can be found in *CALiPER Application Summary Report 16: LED BR30/R30 Lamps*, which is available at <http://www1.eere.energy.gov/buildings/ssl/reports.html>.

⁸ ANSI C78.21-2003, *The American National Standard for Electric Lamps—PAR and R Shapes*, provides dimensional tolerances for directional lamps.

conventional lamps, the designation process can be ambiguous. For LED AR111 lamps, the designation stems from the general shape, size, and base type.

LED AR111 lamps are typically intended to match the physical characteristics of halogen AR111 lamps. They are not replacements for CMH AR111 lamps, although they may be a direct competitor in new installations where energy efficiency is a priority. In replacement applications, it is essential to consider the complete lighting system, which includes at least one transformer and potentially additional dimming controls. As with other low-voltage lighting systems, compatibility of electronic components is a very important consideration.⁹

⁹ Some discussion of compatibility issues can be found in the DOE SSL technology fact sheet, *LED MR16 Lamps*, available at <http://ssl.energy.gov/factsheets.html>.

4 Results

CALiPER Series 17 LED AR111 Test Data

This report analyzes the independently tested performance of five LED lamps labeled as AR111 and one LED lamp labeled as PAR36—all six are denoted as AR111 lamps in this report. Each of the lamps was anonymously purchased in February or March 2012. In this report, they are collectively referred to as the Series 17 products. For more on CALiPER product selection parameters, both in general and as they pertain to this group of products, see Appendix A. It is important to note that attempts were made to obtain several additional lamps for this report; however, many products were not available within the necessary timeframe of approximately three months from ordering until CALiPER processing began. As an emerging product category, it is expected that the variety of LED AR111 lamps will continue to grow.

The Series 17 products—along with two benchmark products—are shown in Figure 1. The exact shape and construction of the lamps varied substantially, with the measured length ranging from 2.20 inches to 3.71 inches. All of the products had a diameter between 4.29 and 4.36 inches. Five of the products were rated for operation at 12 V and had a G53 base, but one product (12-27) described as an AR111 was supplied with an incompatible base (GU10) and was rated for 120 V operation. Product 12-27 could not be used to replace an existing halogen AR111 lamp.

All of the units were tested according to IES LM-79-08, using both an integrating sphere and goniophotometer; for each of the Series 17 products, the difference in measured lumen output between the two methods was less than 2%, which is typical. Except for luminous intensity distribution characteristics, all values included in this report were measured using the integrating sphere method. Two samples of each product were tested, except for product 12-23 for which one sample was tested. All reported values are the mean of the samples; the exception is D_{uv} , which is reported as the value furthest from zero. Table 1 summarizes key results from CALiPER testing. Definitions of many of the terms used in this report can be found in Appendix B.



Figure 1. Photographs of the products in this series of CALiPER testing, including the halogen benchmark (12-22) and the CMH benchmark (12-05).

Table 1. Results of CALiPER tests for the Series 17 LED AR111 lamps. Performance criteria include initial output, total input power, luminous efficacy, power factor, color rendering index (CRI), special color rendering index R_9 , correlated color temperature (CCT), D_{uv} , center beam candlepower (CBCP), beam angle, and field angle. All results are for lamps tested at 12 VAC, except for 12-27, which was tested at 120 VAC.

DOE CALiPER Test ID	Initial Output (lm)	Input Power (W)	Luminous Efficacy (lm/W)	Power Factor ¹	CRI	R_9	CCT (K)	D_{uv}	CBCP (cd)	Beam Angle (deg)	Field Angle (deg)
12-09	537	9.3	58	-	72	-31	5764	0.0080	4117	15	34
12-12	502	10.7	47	-	86	34	3253	0.0000	5688	15	26
12-23	397	10.3	39	-	85	31	2718	-0.0043	869	34	69
12-25	588	10.8	54	-	81	21	2946	0.0014	2016	26	52
12-27	477	15.6	31	0.61	84	22	2954	-0.0006	3262	20	33
12-28	444	8.6	52	-	71	-32	5772	0.0061	2788	18	38
Minimum	397	8.6	31	-	71	-32	2718	-	869	15	26
Mean	491	10.9	47	-	80	8	3901	-	3123	21	42
Maximum	588	15.6	58	-	86	34	5772	-	5688	34	69

1. For low-voltage systems, power factor is a function of both the lamp and transformer.

Previously Tested LED AR111 Lamps

The CALiPER program previously tested two LED AR111 lamps (09-114 and 10-01)—purchased in late 2009 and early 2010—which were included in the Round 11 Summary Report. Appendix C shows the results from previous CALiPER testing. Although the Round 11 AR111 lamps might not be expected to perform as well as newer products, in general they performed as well as some of the Series 17 products, although they are at the low end of the range.

Supplemental LED AR111 Data

ENERGY STAR

Although they are not explicitly covered by ENERGY STAR, some of the performance criteria applied to other types of directional lamps could also be used to evaluate the performance of AR111 lamps. For example, according to the *ENERGY STAR Program Requirements for Integral LED Lamps* (version 1.4), directional LED lamps should have an efficacy greater than 45 lm/W, a nominal CCT between 2700 K and 4000 K, a D_{uv} between -0.006 and 0.006, and a CRI greater than 80, among other criteria. These performance benchmarks are used in this report.

LED Lighting Facts Data

As of July 13, 2012, LED Lighting Facts listed 10 LED AR111 lamps, which were from just two manufacturers—one product from each was tested in Series 17 (12-12 and 12-27). These 10 lamps are just a small fraction of more than 1,000 directional lamps listed by LED Lighting Facts.

Conventional Product Benchmarks

In conjunction with testing of the Series 17 LED products, two conventional benchmarks were tested: one 75 W halogen AR111 and one nominally 35 W CMH AR111. Both were nominally 3000 K and exhibited beam angles of

25° and 22°, respectively. They were measured as having a CBCP of 4,904 cd (halogen) and 7,778 cd (CMH)—importantly, AR111 lamps (like some other directional lamps) are often specified based on CBCP rather than lumen output. More results from the CALiPER benchmark testing can be found in Appendix D.

To supplement CALiPER’s limited testing of conventional AR111 lamps, an informal survey of major conventional lamp manufacturers was conducted. In total, data for 45 AR111 lamps was collected from GE, Philips,¹⁰ and OSRAM SYLVANIA—38 of the products were halogen and 7 were CMH. Table 2 provides summary results reflecting the performance of these products. Importantly, some of the provided information was nominal values. Nonetheless, this characterization is necessary to establish parameters of typical AR111 performance and set color quality and luminous intensity distribution targets for LED AR111 performance. For comparison, this dataset is included in many of the charts found in this report.

Table 2. Summary information for the performance of halogen and CMH AR111 lamps. The data represents 38 halogen products from GE, Philips, and OSRAM SYLVANIA, as well as 7 CMH products from Philips. Lumen output was not provided for any of the surveyed halogen AR111 lamps.

		Initial Output (lm)	Input Power ¹ (W)	Luminous Efficacy (lm/W)	CRI	CCT (K)	CBCP (cd)	Beam Angle (deg)	Rated Lifetime (hours)
Halogen	Minimum		35		100	2800	1,400	4	3,000
	Mean		60		100	2937	15,068	19	3,211
	Maximum		100		100	3000	48,000	45	4,000
CMH	Minimum	650	20	25	81	2900	4,000	10	9,000
	Mean	1807	48	30	82	2979	20,214	23	9,857
	Maximum	2850	70	34	85	3050	50,000	40	11,000

1. This listed input power is the nominal wattage of the lamp, not including the transformer or ballast.

¹⁰ Philips’ literature describes the included lamps as R111s. These lamps have a different base type (GX8.5) and require an external ballast. As previously noted, they are not interchangeable with halogen AR111 lamps. Additionally, Philips was the only manufacturer surveyed who sold CMH “AR111” lamps.

5 Analysis

Lumen Output and Efficacy

The Series 17 LED AR111 lamps had measured output ranging from 397 to 588 lumens, with a mean of 491 lumens. As shown in Figure 2, this range is lower compared to that of the CMH AR111 lamps. It is also lower compared to halogen AR111 lamps, although lumen output data was not published for any of the halogen lamps surveyed. Based on the efficacy of the halogen AR111 benchmark (BK12-22, 11.7 lm/W), the range of lumen output for the LED AR111 lamps only matches the lowest wattage halogen lamps (35 W), with perhaps some matching 50 W halogen AR111 lamps. As previously noted, however, AR111 lamps are more often specified using CBCP.

Four of the six Series 17 LED AR111 lamps exceeded the 45 lm/W threshold required of directional lamps for ENERGY STAR qualification, although ENERGY STAR does not explicitly cover AR111 lamps. These four products (47 to 58 lm/W) were substantially more efficacious than typical CMH (25 to 40 lm/W) and halogen (10 to 20 lm/W) AR111 lamps. The remaining two LED AR111 lamps (31 and 39 lm/W) were similar to the surveyed CMH AR111 lamps. Notably, the efficacy of the CALiPER-tested AR111 lamps was generally lower than for the Series 16 LED BR30/R30 lamps.

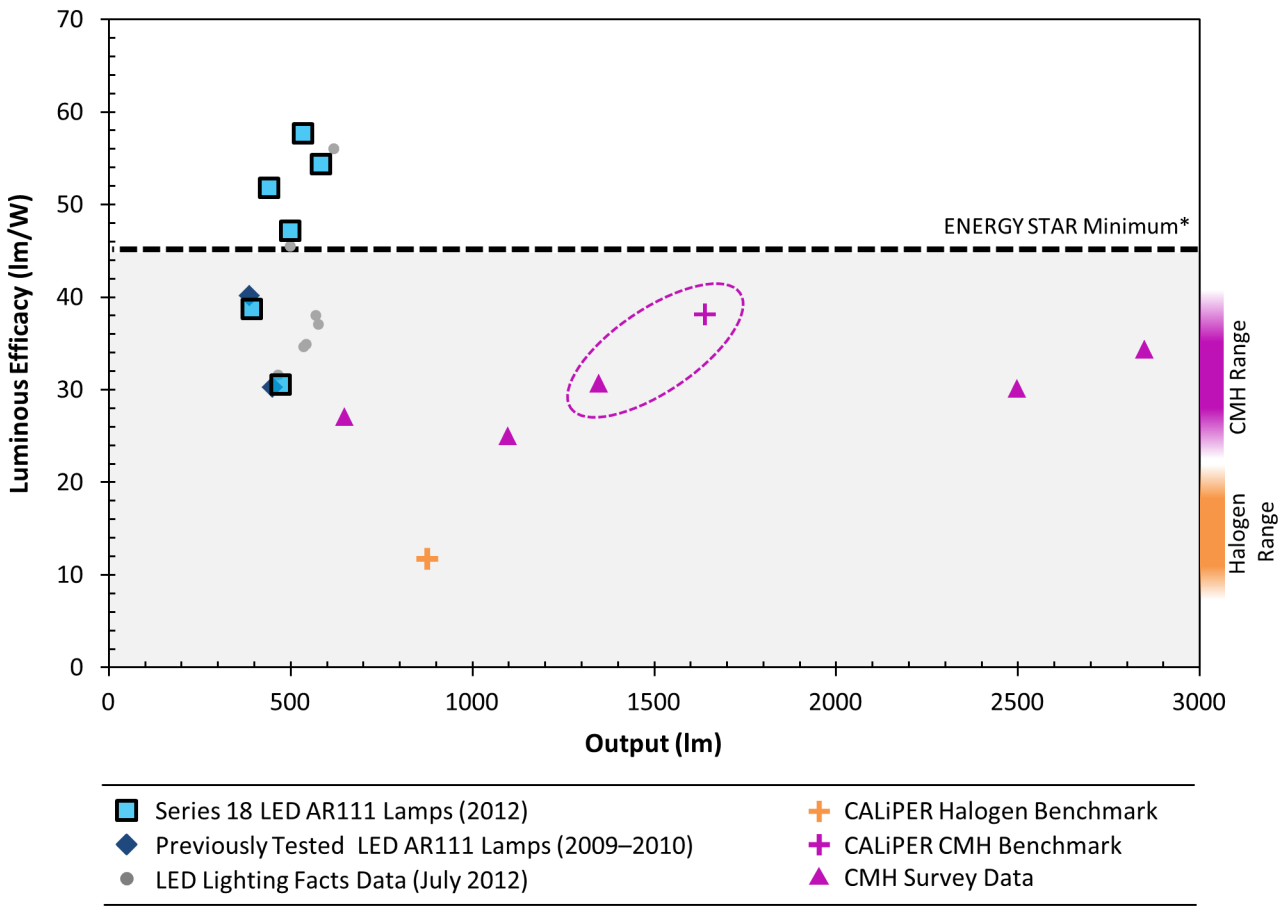


Figure 2. Luminous efficacy versus lumen output. Although some of the Series 17 LED AR111 lamps had luminous efficacies that are favorable compared to halogen and CMH products, they did not provide the same lumen output. The dashed oval encloses data for the same lamp as listed by the manufacturer and as tested by CALiPER. *ENERGY STAR criteria for directional lamps are not explicitly applicable to AR111 or PAR36 lamps.

Distribution of Light

Luminous intensity distribution is a fundamental characteristic used when specifying AR111 and other directional lamp types. In particular, AR111 lamps are known for having narrow distributions with relatively defined edges to the beam. Many of the surveyed halogen AR111 lamps (17 of 38) had a nominal beam angle between 4° and 8°, with 14 having a beam angle of 24° and the remaining seven products having a beam angle of approximately 40°. The surveyed CMH AR111 lamps had listed beam angles ranging from 10° to 40°, not matching the very narrow beam angles available in halogen lamps. All of the Series 17 LED AR111 had beam angles between 15° and 34° (see Figure 3); Like the CMH products, the LED lamps did not have very narrow beam angles.

Although beam angle is an important metric, it cannot fully characterize a lamp's luminous intensity distribution. Importantly, the pattern of light created by a typical AR111 lamp has a sharp edge to the cone of emitted light; that is, the beam has a relatively hard edge rather than fading gradually at the beam edge. This characteristic can sometimes be inferred by examining the relationship between beam angle and field angle. Based on numerical data it is unlikely that products 12-23 and 12-25 replicate the beam appearance of a traditional halogen AR111 lamp; they may be more similar to CMH AR111 lamps.

Not all aspects of a luminous intensity distribution can be captured numerically. In some applications, the smoothness of the beam pattern from the center to the edge can be very important. This characteristic lacks a metric, but adjectives such as *smooth*, *spotty*, or *uneven* are sometimes used. This attribute was not analyzed as part of this series of CALiPER testing.

As with other directional lamp types, there is a clear relationship between beam angle and CBCP: as beam angle increases, CBCP decreases (see Figure 4). Importantly, at any given beam angle, the CBCP of the Series 17 LED AR111 lamps could not match the CBCP of conventional lamps. In part, this can be attributed to the lower lumen output of the LED AR111s.

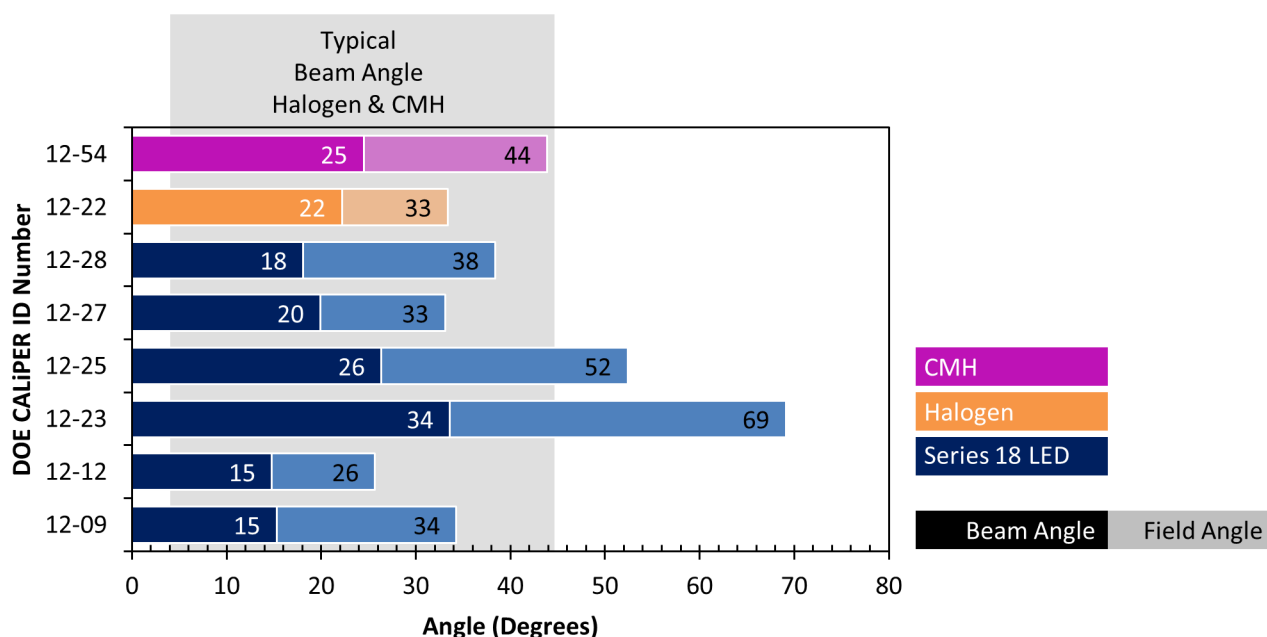


Figure 3. Beam angle and field angle of the Series 17 LED lamps compared to CALiPER benchmarks. The typical nominal beam angles are based on a review of manufacturer literature.

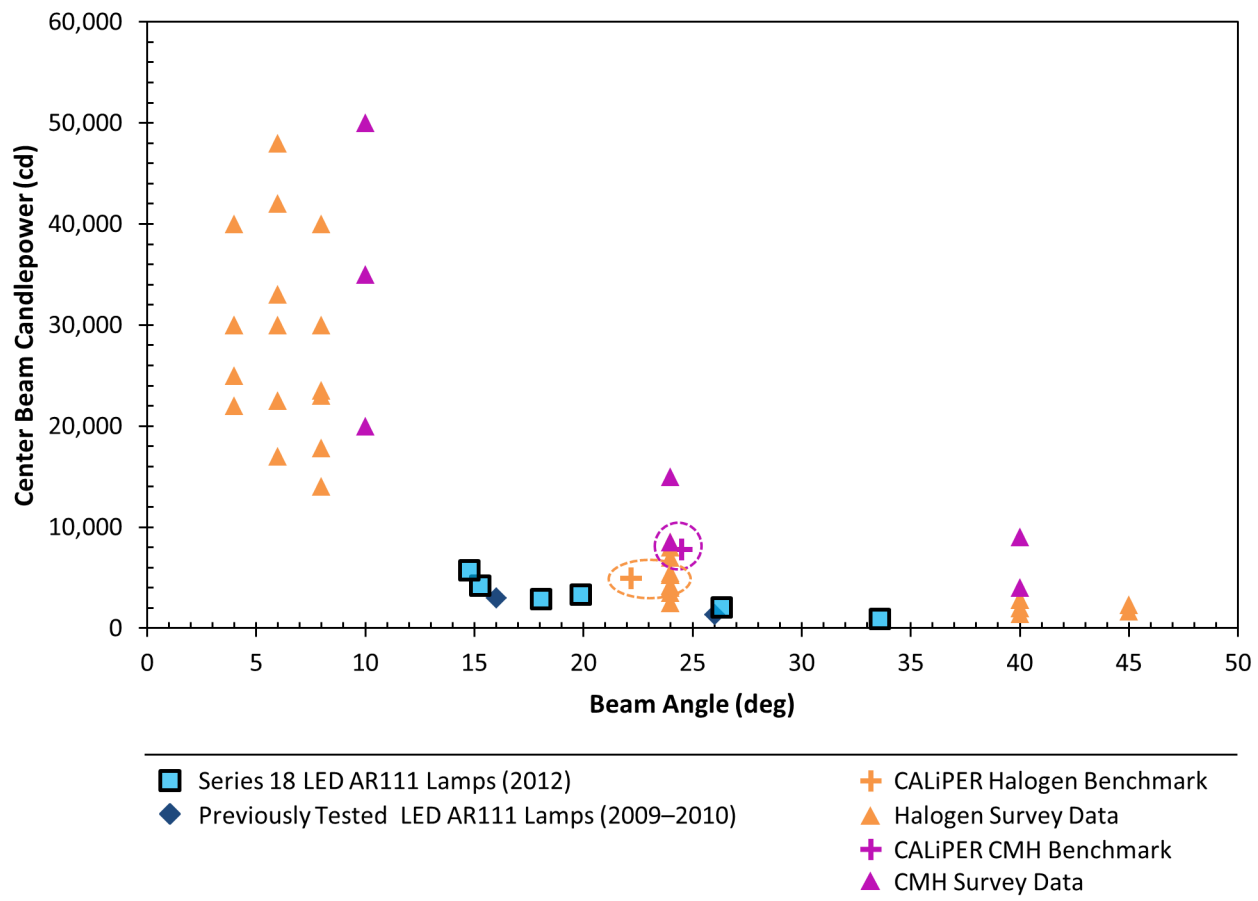


Figure 4. Center beam candlepower (CBCP) versus beam angle. At any given beam angle, the Series 17 LED AR111 lamps cannot match the maximum intensity of halogen or CMH lamps. The dashed ovals enclose data for the same lamps as listed by the manufacturer and as tested by CALiPER.

Color Characteristics

Because AR111s are most often used for object lighting, color quality is especially important. Of particular significance is performance relative to halogen lamps, which are the incumbent technology in this application category. The CCT of the Series 17 LED AR111 lamps ranged from 2718 K to 5772 K, as shown in Figure 5. Only three of the six products had a nominal CCT of 2700 K or 3000 K,¹¹ which matches typical halogen AR111 lamps. One product had a nominal CCT of 3500 K, and two products had a nominal CCT of 5700 K. Although higher CCTs may be desired for some applications, these products may not provide suitable illumination for those seeking a direct replacement for a halogen AR111 lamp.

Each of the Series 17 LED products had a CRI between 71 and 86, with four products having a CRI above 80. The two products (12-09 and 12-28) with a CRI near 70 cannot be considered effective replacements for conventional AR111 lamps—this level of performance is typically only appropriate in some exterior applications. None of the AR111 lamps listed by LED Lighting Facts had a CRI less than 80, although four of the ten had a CCT of 4000 K or higher.

¹¹ Nominal CCT ranges are defined in ANSI C78.377-2008.

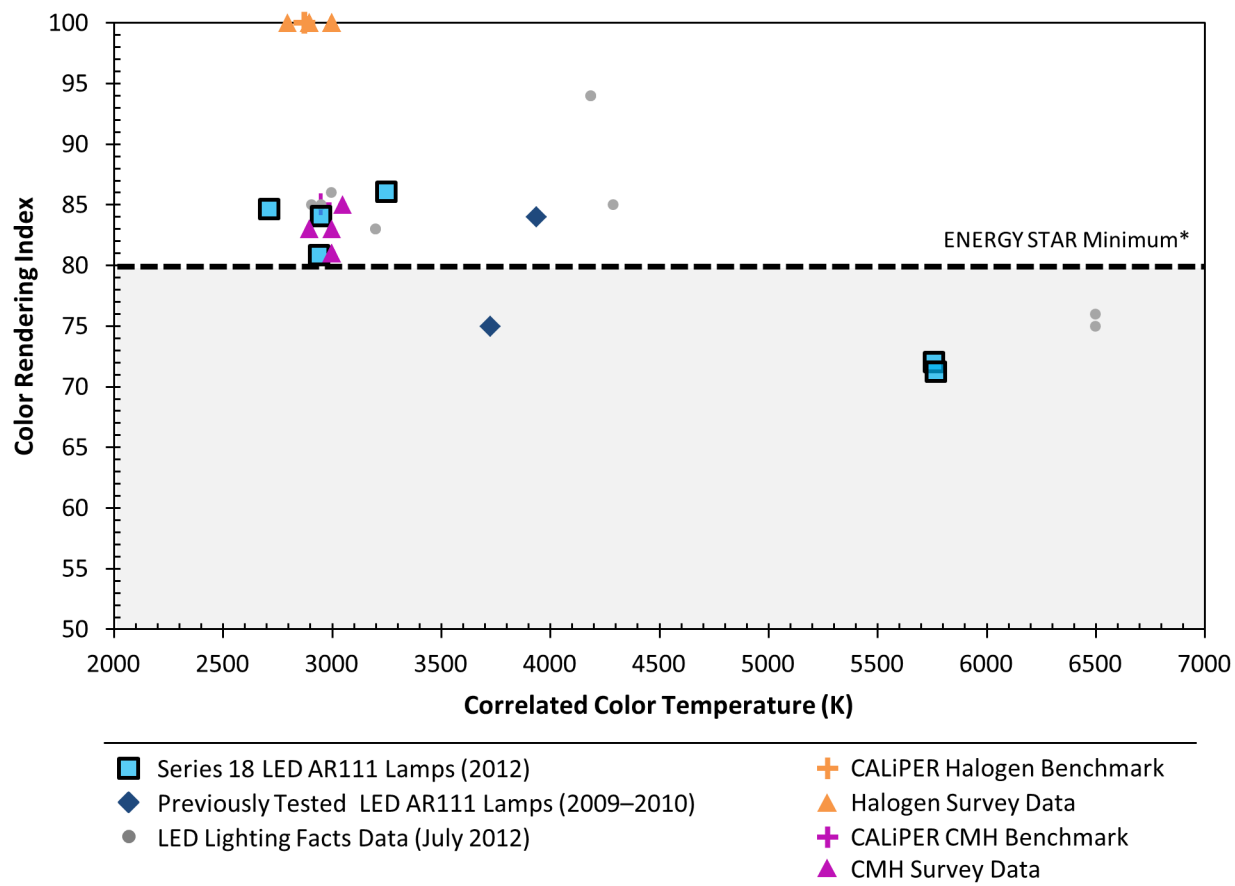


Figure 5. Color characteristics of the Series 17 LED AR111 lamps compared to other data. Many of the Series 16 lamps had color characteristics similar to incandescent BR30/R30 lamps. *ENERGY STAR criteria for directional lamps are not explicitly applicable to AR111 or PAR36 lamps.

Similar to other recent CALiPER testing, the measured R_9 values for the Series 17 LED AR111 lamps had a strong linear correlation with CRI ($r = 0.98$). Both products that had a CRI below 80 had an R_9 less than zero. The remaining products with CRIs in the 80s had R_9 values between 21 and 34.

Much like luminous efficacy, the color quality attributes of the Series 17 LED AR111 lamps were not as good as the Series 16 LED BR30/R30 lamps. The AR111 form factor would not necessarily require the use of different LED packages than are in the BR30/R30 lamps, so the performance gap is unlikely to have been caused by a technical issue. Rather, it may be an indication of manufacturers giving lower priority to these lamps because of low market share, or of a difference in the subset of manufacturers offering AR111 LED lamps.

Electrical Characteristics

Alternating Current (AC) versus Direct Current (DC) Operation

According to the manufacturer's literature for product 12-25, the lamp would operate differently if supplied with 12 VAC power instead of 12 VDC power. To investigate this claim, photometric testing was conducted under both conditions for both product 12-25 and a second product, 12-23. The results are shown in Table 3. Despite claims to the contrary, CALiPER testing revealed nearly identical performance. However, various lamp-transformer combinations may perform differently.

Table 3. Comparison of operation with AC and DC supply. Despite the claim of the manufacturer of product 12-25, there was little difference between operation at 12 VAC or 12 VDC. For product 12-23, one sample was tested in the AC configuration and two were tested in the DC configuration; this is likely the cause of the small variation in some values.

DOE CALiPER Test ID	Initial Output (lm)	Input Power (W)	Efficacy (lm/W)	Power Factor	CRI	R ₉	CCT (K)	D _{uv}	CBCP (cd)	Beam Angle (deg)	Field Angle (deg)
12-23 AC	397	10.3	39	0.62	85	31	2718	-0.0043	869	34	69
12-23 DC	391	10.2	38	NA	84	30	2701	-0.0043	876	32	64
12-25 AC	588	10.8	54	0.61	81	21	2946	0.0014	2,016	26	52
12-25 DC	592	10.7	55	NA	81	21	2933	0.0011	2,043	26	52

Manufacturer Claims

Evaluating the accuracy of manufacturers' performance claims is an important component of the CALiPER program. This task is often difficult because different values are reported in different literature. For example, performance values listed on specification sheets are sometimes different from values listed by LED Lighting Facts or on product packaging. In some cases, these differences may be attributable to rounding to simplify visual appearance or improve legibility. Alternatively, nominal values may be used instead of a single specific test result to better reflect the distribution of performance that can be expected from lighting products (i.e., not every product is identical). In other cases, updates to products may not be immediately reflected in product literature. For example, one of the Series 17 products (12-12) had an old specification sheet that did not match LED Lighting Facts data (which was very similar to the CALiPER-measured performance). Given the status of LED lighting as an emerging technology, it is especially important for all manufacturer literature to represent the true performance of a product. If it does not, consumers may end up with products that do not meet their expectations.

Among other differences in input power and efficacy, two products (12-09 and 12-27) emitted less than 90% of the lumens claimed by the manufacturer,¹² and only one product was measured to be accurate for lumen output, input power, and efficacy. Perhaps more interesting, of the four products that listed a beam angle, all were measured to have a smaller beam angle than claimed. In three cases, the difference was greater than 20% (15° versus 25°, 15° versus 25°, and 18° versus 30°), but in the fourth case the difference was fairly small (20° versus 24°). Conventional directional lamps have specific tolerances for beam angle that acknowledge the variability in manufacturing, especially for glass components. Although there is also variability in the manufacture of LED lamps, the discrepancies for this series of testing go beyond a reasonable tolerance, such as the ±6° allowed for PAR and MR lamps of a similar beam angle.

Equivalency Claims

Especially for those with less experience and knowledge of lighting metrics, equivalency claims may be a key factor for purchasing. Two of the six Series 17 products (12-12 and 12-25) made claims of equivalency to a

¹² The ±10% criterion is used by CALiPER and LED Lighting Facts for determining accuracy; it is notably lenient for some metrics and may not match other standards. This evaluation does not imply that conventional products meet this level of accuracy. Regardless, it is especially important for new technologies to perform as expected.

specified wattage halogen lamp (50 W and 75 W, respectively). Although equivalency entails much more than lumen output, it is the easiest metric to use when evaluating the accuracy of these claims—in actuality, given the importance of distribution for directional lamps, equivalency claims are insufficient and may be misleading. At 502 lumens, the equivalency claim for product 12-12 was within 10% of the lumens emitted from a typical 50 W AR111 halogen lamp. In contrast, product 12-25 emitted only 588 lumens, which was much less than the 877 lumens emitted by the 75 W halogen benchmark (BK12-22) that had the same nominal beam angle.

6 Conclusions

Six LED AR111 lamps were tested by CALiPER. This is a smaller quantity than for other CALiPER application summary reports, and reflects the difficulty in obtaining these products. The AR111 form factor is a niche product that is used infrequently in the United States, potentially limiting the market for LED AR111s. However, manufacturers seem to be increasingly considering this market. Some aspects of conventional halogen AR111 lamp performance can be met by LED lamps, but the current generation of products is somewhat limited:

- The lumen output of each of the products was equivalent to only 35 W or 50 W halogen AR111 lamps—all of the products emitted between 397 and 588 lumens. Lumen output did not approach that of 75 W or 100 W halogen AR111 lamps. Perhaps more importantly, the Series 17 LED AR111 lamps generally did not match the CBCP of comparable halogen lamps.
- The Series 17 products had luminous efficacies between 31 and 58 lm/W. Although this is favorable compared to halogen lamps, not all of the products were more efficacious than CMH AR111 lamps and the overall efficacy range was lower than other LED directional lamp categories.
- All of the beam angles were within the range of typical halogen AR111 lamps, although none of the tested products could match conventional products with narrow distributions (i.e., 10° or less), a hallmark of AR111 lamps. Other aspects of the specialized AR111 lamp distribution could not easily be quantified.
- Two of the six products had a CCT above 5000 K and a CRI less than 80; these lamps would not make effective replacements for halogen AR111 lamps. The remaining four products all had a CRI in the 80s and a CCT near 3000 K; these lamps could be used in general illumination applications, but may not be satisfactory for applications that demand high color quality (e.g., museums, hospitality, or retail), where AR111s are most often used.
- One Series 17 lamp had a different base (GU10) than either halogen or CMH AR111 lamps. It was also much longer than conventional halogen AR111 lamps and operated at line voltage rather than low voltage. It would not function as a replacement lamp.

Given their overall performance characteristics, most—if not all—of the Series 17 LED AR111 lamps are unlikely to be effective replacements for halogen AR111 lamps. This is mostly a result of color quality and luminous intensity distribution characteristics. In some applications, they may perform acceptably—and could provide some energy savings—but continued improvement in this market category is warranted. Notably, LED AR111 products from many major conventional lamp manufacturers were not available for inclusion in this series of testing.

Appendix A: Product Selection

Product selection is an important part of the CALiPER process. Products are selected with the intent of capturing the current state of the market—a cross section ranging from expected low to high performing products with the bulk characterizing the middle of the range. However, the selection does not represent a statistical sample of all available products.

Product selection starts with a review of the technology. Beyond relying on professional experience, the team surveys:

- Trade publications, including *Lighting Design + Application*, *LEDs Magazine*, *Mondo ARC*, and *Architectural Lighting*
- Internet websites, including Elumit, DesignLights Consortium, ENERGY STAR, LED Lighting Facts, ESource, and Lightsearch
- National retailers, including Grainger, Goodmart, The Home Depot, Lowe's, Amazon, and Sears
- Other sources, including trade shows (local and national) and manufacturers' representatives

After surveying available products, the CALiPER team characterizes the features of the products and determines what can be standardized to ease comparison. For this report focusing on AR111 lamps, the following features were evaluated and led to the final selection:

- Distribution – Beam angle was the first consideration for Series 17 product selection, with preference given to narrower distributions. However, the only LED AR111 lamps found had listed beam angles between 24° and 30°. Benchmark halogen and CMH AR111 lamps with similar beam angles were selected to allow for direct comparison, despite the fact that narrow beam angle conventional AR111 lamps are more prevalent.
- CBCP – Manufacturers of halogen AR111 lamps typically list the CBCP rather than lumens; in contrast, most LED manufacturers list the lumens and not CBCP. Therefore, it was not possible to use CBCP as a selection criterion.
- Lumen package – The target lumen output for the Series 17 LED AR111 lamps was 350 to 800 lumens, or approximately the range of 35 W to 75 W halogen AR111 lamps. Most LED AR111 lamps were offered at only one wattage/lumen output, so choice was very limited.
- Color temperature – A CCT of 2700 to 3000 K, representative of halogen sources, was selected if an option was available.
- Lamp diameter/shape/base – The Series 17 products had to be advertised as AR111 or PAR36 replacements and mimic the form of traditional halogen AR111 lamps.

Other non-performance related criteria are also considered:

- Product availability – As a federally funded program, CALiPER focuses on products available in the United States.
- Energy efficiency programs – Some emphasis is given to including products listed by large energy efficiency programs (e.g., ENERGY STAR).

After establishing a list of appropriate products, attempts are made to anonymously purchase the products through standard industry resources (e.g., distributors, retailers). Sometimes, products are not available or cannot be shipped in a timely manner. Thus, the final group of products tested does not always match the intended results of the selection process.

Appendix B: Definitions

Beam Angle Degrees (°)	The angle between the two directions for which the intensity is 50% of the maximum intensity (ANSI/IES RP-16-10) or center beam intensity (ANSI C78.379-2006), as measured in a plane through the beam axis. For example, if the maximum intensity is 1000 cd, the angle at which the intensity is 500 cd is half of the beam angle. If 500 cd occurs at 20° from center beam, then the beam angle is 40°.
Center Beam Candlepower (CBCP) Candela (cd)	The luminous intensity at the central axis of the beam, which typically corresponds to a vertical angle of 0° (called nadir for lamps oriented downward). Although candlepower is a deprecated term, it is still widely used in this context.
Correlated Color Temperature (CCT) Kelvin (K)	The absolute temperature of a blackbody radiator having a chromaticity that most nearly resembles that of the light source. CCT is used to describe the color appearance of the emitted light.
Color Rendering Index (CRI or R_a)	A measure of color fidelity that characterizes the general similarity in color appearance of objects under a given source relative to a reference source of the same CCT. The maximum possible value is 100, with higher scores indicating less difference in chromaticity for a sample of eight color samples illuminated with the test and reference source. See also: <i>Special Color Rendering Index R₉</i> .
D_{uv}	The distance from the Planckian locus on the CIE 1960 UCS chromaticity diagram (also known as u', 2/3 v'). A positive value indicates the measured chromaticity is above the locus (appearing slightly green) and a negative value indicates the measured chromaticity is below the locus (appearing slightly pink). The American National Standards Institute provides limits for D _{uv} for nominally white light.
Luminous Efficacy Lumens per watt (lm/W)	The quotient of the total luminous flux emitted and the total input power.
Field Angle Degrees (°)	The angle between the two directions for which the intensity is 10% of the maximum intensity (ANSI/IES RP-16-10) or center beam intensity (ANSI C78.379-2006), as measured in a plane through the beam axis. For example, if the CBCP is 1000 cd, the angle at which the intensity is 100 cd is half of the field angle. If 100 cd occurs at 32° from center beam, then the field angle is 64°.
Input Power Watts (W)	The power required to operate a device (e.g., a lamp or a luminaire), including any auxiliary electronic components (e.g., ballast or driver).
Luminous Intensity Distribution Candela (cd)	The directionality of radiant energy emitted by a source, which may be shown using one of several techniques. It is most often presented as a polar plot of the candelas emitted in a vertical plane through the center of the lamp or luminaire.
Output Lumens (lm)	The amount of light emitted by a lamp or luminaire. The radiant energy is weighted with the photopic luminous efficiency function, V(λ).
Power Factor	The quotient of real power (watts) flowing to the load (e.g., lamp or fixture) and the apparent power (volt-amperes) in the circuit. Power factor is expressed as a number between 0 and 1, with higher values being more desirable.

**Special Color
Rendering Index R_9**

A measure of color fidelity that characterizes the similarity in color appearance of deep red objects under a given source relative to a reference source of the same CCT. The maximum possible value is 100, with higher scores indicating less difference in chromaticity for the color sample illuminated with the test and reference source. R_9 and R_a (CRI) are part of the same CIE Test-Color Method, but the R_9 color sample is not included in calculation of R_a .

Appendix C: Previous CALiPER Testing of AR111 LED Lamps

Table C1. Summary data for previous CALiPER tests of LED AR111 lamps. The first two digits of the CALiPER Test ID indicate the year in which the product was purchased.

DOE CALiPER Test ID	Initial Output (lm)	Input Power (W)	Efficacy (lm/W)	Power Factor	CRI	CCT (K)	CBCP (cd)	Beam Angle (deg)	Field Angle (deg)
09-114 ¹	451	14.9	30	NA	75	3727	1,381	26	56
10-01	388	9.6	40	0.68	84	3937	2,988	16	34

1. Tested at 12 V DC

Appendix D: CALiPER Testing of Conventional AR111 Lamps

Table D1. Summary data for CALiPER tests of benchmark conventional AR111 lamps. The first two digits of the CALiPER test ID indicate the year in which the product was purchased.

DOE CALiPER Test ID	Source Type	Voltage	Initial Output (lm)	Input Power (W)	Efficacy (lm/W)	Power Factor	CRI	CCT (K)	CBCP (cd)	Beam Angle (deg)	Field Angle (deg)
BK12-22	Halogen	12	877	75.1	12	0.96	100	2875	4,904	22	33
BK12-05	CMH	120	1,643	43.2	38	0.94	85	2952	7,778	25	44

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